# APPLICATION OF PCE VALUES IN CAPACITY AND LOS ANALYSIS

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**ABSTRACT**

Roadway capacity is the maximum flow reached at critical density when quantified and is the maximum flow reached at optimum speed when measured qualitatively in LOS analysis. PCE could be construed as a function of (independent variables) traffic flow, heavy vehicles, roadway, traffic and ambient conditions. The conditions vary singularly or in combination from road section to section or point to point, probably explaining why PCE values are merely approximations of the effects of vehicle-mix. The study is intended to show that PCE values vary relative to prevailing conditions hence should not be taken as fixed values except in the unlikely situation of homogeneous traffic stream. The paper explored the effects of poor level terrain on PCE values under daylight and clear weather conditions. Standard PCE values were compared with simulated empirical PCE values obtained from 6 sites in Malaysia using headway method. Based on the hypothesis that PCE values differ significantly between roadway with and without vertical deflections; the study found substantial changes in PCE values and concluded that, ignoring PCE modifications could lead to grossly inaccurate capacity and level of service estimate with attendant consequences for traffic and transportation modelling.

## 1. INTRODUCTION

The road network is a maze of links and intersections, and each with its own physical characteristics that influence traffic flow under prevailing conditions. Highway Capacity Manual - HCM special- report 209 (*4*) defines highway capacity as 'the maximum hourly rate at which vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions'. The definition recognises and rightly so, the potential for substantial variations in flow during an hour, and focuses analysis on intervals of maximum flow. However, the definition missed vital elements (maximum flow and critical density) that define highway capacity and focuses on level of service based capacity (maximum flow and optimum speed). In any case the definition suggests that highway capacity can be a point of section measurement, which is quite interesting and valid, because highway capacity is a point or section measurement under prevailing conditions.

Since highway capacities vary from point to point, section to section, it can be argued that applied passenger equivalent (PCE) values in the capacity and level of service analysis would also vary. Passenger car equivalent values are measures of vehicle performances. Their use is central to highway capacity and LOS analysis where mixed traffic streams are present. By applying PCE values in highway capacity and level of service (LOS) analysis, in essence attempts are made to determine the number of passenger cars displaced in the traffic flow by non passenger cars like motorcycle, light goods vehicles, buses, trucks, and heavy goods vehicles under prevailing roadway, traffic and ambient conditions. This is to be expected because qualitative and quantitative measurements of traffic flow are constrained by prevailing conditions. Thus, the assertion that PCE values are somehow fixed for terrain type, road geometry, directional distribution, and traffic conditions is somehow faulty because road, traffic and ambient conditions are known factors that affect highway capacity it can be argued.

Overtime scholars have argued about the definition and bases for numerical derivation of PCE values. In fact many researchers have tried to quantify the effect of non-passenger cars on traffic flow relying on HCM approach but using different methodologies and equivalency criteria. A few of those studies utilized field data, while most employed traffic simulation to derive PCEs for a wide range of conditions often with doubtful and exaggerated outcomes.

However, the paper is not about derivation of PCE values, rather it focuses on the correct application of dynamic PCE values in highway capacity and LOS analysis given poor road surfacing conditions. It explored the effects of poor level terrain on PCE dynamic values under daylight and clear weather conditions. In the paper, a simplistic headway method was used to modify standard Malaysia PCE values for highway capacity and level of service analysis using empirical data from 6 field study sites.

Malaysia's road system is extensive and is among the finest in Asia. It covers a distance of 63,445 km with about 5.2 million total numbers of registered vehicles at the end of 1990. The inter-urban North-South Expressway, New Klang Valley Expressway (NKVE) and the Federal Highway Route 2 (FHR2) are the largest road transportation infrastructure in Peninsula Malaysia. The 848 km expressway links major industrial areas to urban centres commencing from Bukit Kayu Hitam to Johor Bahru. The East-West Highway serves as part of the Asian Highway System linking Thailand with Malaysia. In 1993, there were 5.4 million motor vehicles of which 38.6% were motorcars, 54.8% motorcycles and 6.6% goods vehicles. This increased by 50.5% to reach 8.1 million motor vehicles in 1997, with motorcycles accounting for 53% of the total, followed by motorcars 40% and goods vehicles 7%. In other to improve the efficiency and effectiveness of road services, application of PCE in capacity analysis must be modified to reflect prevailing conditions.

## 2. QUANTITATIVE ASSESSMENT OF ROAD TRAFFIC OPERATION

For the purpose of measuring *quantity*, the parameters, density and flow are important, because density is a finite element that describes the number of vehicles per unit length of the road. Flow which is the number of vehicles passing a given point on or road section per unit time measures the traffic stream quantity and traffic flow demand. In essence, quantitative assessment of road traffic operation can be construed as traffic flow and capacity measurements. Estimating highway capacity is not without problems, according to Minderhoud *et al (7),* the problem consists of a series of essential points of interest that include among others; Type of Data To Be Collected, Location Choice for Observations, Choice for Appropriate Averaging Interval, Needed Observation Period, Required Traffic State, and Lane.

Capacity-estimation problem can be divided into two categories: the direct-empirical studies and indirect-empirical methods noting that all the methods are a mixture of observation and theory. It could be argued that some methods have more theoretical justification than others especially those that have to contend with probabilistic functions. For example the basic principle capacity estimation using headway models is deterministic, relying on parameters of the compound probability density function of headways with results that may not bear resemblance to the practical value. Consider equations 1 and 2 below.

$$q = uk \qquad (1)$$

$$q = -\beta_o + \beta_1 k - \beta_2 k^2 \qquad (2)$$

Where; q is flow, u is speed, k is density, $\beta_o$ is a constant, $\beta_1$ and $\beta_2$ are coefficients; $\beta_o$ describes roadway density, $\beta_1 k$ describes vehicle speed while $\beta_2 k^2$ describes traffic flow.

In order not to violate the rules of concavity, traffic flow rates are constrained within finite density boundaries (0 and $k_j$) as contained in many literatures. Whether traffic is operating at congested or uncongested state, the operations are contained with the finite density boundaries. These finite boundaries cannot be exceeded, also the critical density ($k_c$) cannot be $k_j$ divided by 2 because the concavity is not symmetrical, speeds are not the same for the congested and uncongested sectors (see Figure 1).

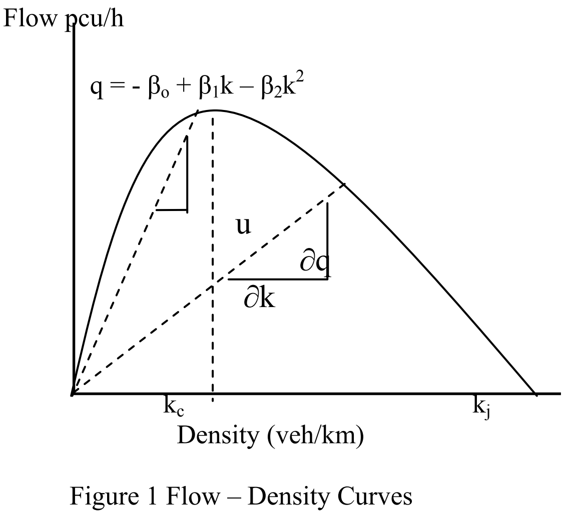


Figure 1 Flow – Density Curves

## 3. QUALITATIVE MEASUREMENT OF ROAD SERVICE

Road network is a maze of nodes (intersections) and links; each with its own physical characteristics that influence prevailing traffic flows from point to point, section to section. Travel time is what most road users are concerned about. It is a useful guide for measuring the effectiveness of roads; when used in conjunction with delay and capacity utilisation; the quality of service can be assessed. As the quality of service decreases, so will the average travel speed, drivers will experience more delays, platooning becomes intense as density increases. That being the case, it can be asserted that the mixed-traffic stream harmoniser (PCE) would also vary relative to the prevailing road, traffic and ambient conditions. Consider equation 3 below,

$$u = -\,{}^{\beta_o}/_{k} + \beta_1 - \beta_2 k \qquad (3)$$

Because ${}^{\beta_o}/_{k}$ is small and negligible equation 3 can be rewritten as;

$$u = \beta_1 - \beta_2 k \qquad (4)$$

Let, $k = {}^{q}/_{u}$; $\beta 1 = u_f$ and $\beta_2 = \frac{\partial_u}{\partial_q}$

For the uncongested traffic state ($u_u$);

$$u_u = u_f - \left[\frac{\partial_u}{\partial_q}\right].\frac{q}{u} \qquad (5)$$

For the congested traffic state ($u_c$);

$$u_c = \int_0^{q_m} \frac{\partial_u}{\partial_q} q \qquad (6)$$

In qualitative measurement of road service, speed is a function of flow, equation 5 is a negative linearity curve with maximum ($u_f$) and optimum ($u_0$) speeds as extreme values, so it's only applicable to the uncongested portion of the speed-flow curve in figure 2 below. The linear function is also constrained by free flow speed ($u_f$) and maximum traffic flow ($q_m$) boundaries if linear rules are not to be violated. Within this section, highway traffic operates in uncongested flow mode with speed oscillating between $u_f$ and $u_0$. However, once absolute highway capacity is reached at optimum speed, additional vehicles in the traffic stream will trigger congested traffic flow mode where vehicle speeds become unpredictable. Whilst in uncongested mode, speed-flow curve oscillates between free flow speed and optimum speed; once the optimum speed is reached and surpassed perturbation sets in, oscillation movement stops; the positive linear curve goes into a coil and recoil mode. In any case, should highway prevailing conditions improve, traffic disturbances removed, and optimum speed reached then the curve balloons back to optimum speed and starts to oscillate again. The sequence can be repeated many times especially in urban areas and city centres.

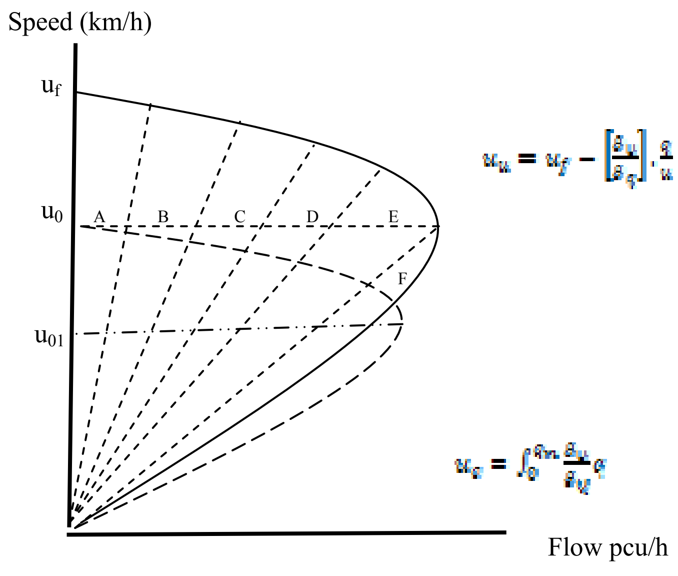


Figure 2 Hypothetical Speed-Flow Curves and LOS

Traffic volume and speed relationship is relied on in Highway Capacity Manual – HCM for the purpose of qualitative measurement of road service often termed Level of Service (LOS) in many literatures. The major problems with speed and volume estimation are two folds; firstly, it is notoriously difficult to estimate optimum speeds, attempts to simulate will often lead to exaggerated speeds with little or no resemblance to that observed; and secondly, optimum speed cannot be exceeded under uncongested traffic flow condition as often the case with LOS E. Uncongested flow terminates at optimum speed.

Although, the maximum flow at optimum speed is often taken as roadway capacity, strictly speaking its service volume aimed at measuring the quality of road service provided. Quantity as a finite element is a function of density and can only be used to measure highway capacity; beside, the equations that govern speed/flow curve do not suggest quadratic function, rather they points to negative linearity curve above and positive linearity curve below optimum speed horizon as shown in figure 2.

So, unlike the flow-density curve where congested and uncongested traffic flows operate within the concave curve finite boundaries; speed-flow curve has two distinct linear functions (negative for uncongested flow and positive for congested flow mode). So, the suggestion that LOS A to E have common optimum speed as prescribed in many literatures, distort the forceful assertion that congested and uncongested traffic flows have different optimum speeds.

## 4. APPLICATION OF PCE VALUES

The term 'passenger car equivalent' was first introduced in the 1965 Highway Capacity Manual. It was defined as 'the number of passenger cars displaced in the traffic flow by truck or a bus under the prevailing roadway, traffic and ambient conditions. This definition still holds today. Since mixed traffic stream is characterised by a variety of transport modes, vehicle volume per hour are converted into passenger car equivalent flows. PCE values for road sections with poor surfacing would obviously not be the same as those of the road sections with good surfacing, so care should be taken when applying these values.

PCE estimation methods can be summarised as; PCEs based on headways used by Cunaign (*1*), PCEs based on delay used by Cunaign (*1*), PCEs based on platoon formation used by Van Aerde and Yagar (*14*), PCEs based on speed used by Van Aerde and Yagar (*14*), PCEs based on vehicle-hours used by Sumner *et al* (*13*) and PCEs based on travel time used by Keller and Saklas (*6*). In fact Elefteriadou *et al* (*4*) in their work on development of PCE for highways suggested that of the techniques mentioned above, speed and delay were the most often used as basis for calculating PCEs on various highway types. Elefteriadou *et al* (*4*) used speed for calculating PCEs because they claim that 'speed is a performance measure immediately experienced by all uses on each type of highway, and it provides a clear picture of how smoothly a facility is operating'. This approach was suggested on the ground that speed is the principal criterion for designation of levels of service.

Van Aerde and Yagar (*14*) developed PCEs based on speed on the basis of relative rates of speed reduction related to each vehicle type. In the United Kingdom, and Malaysia, pre-determined passenger car equivalency values are usually applied to traffic volumes when converting from vehicles per hour. According to Seguin, Crowley and Zwieg *IR, (1998)* PCEs can be defined as the ratio of the mean lagging headway of a subject vehicle divided by the mean lagging headway of the basic passenger car. The headway method is one of the several techniques for measuring PCEs. By using the headway method one is implying that the relative amount of space occupied by a vehicle in motion is the basis for calculating PCE values. Headway is the distance from rear bumper of the lead vehicle to the rear bumper of the following vehicle at appoint in time. It is also a measure of separation between vehicles, which may affect safety and the ease with which pedestrians and vehicles can cross the traffic stream.

Since PCE values are central to roadway capacity calculation it follows that reduction in vehicle speeds resulting from pavement distress would also have effects on the PCE values. This was to be expected as vehicle speeds were lowered almost uniformly on road sections with poor surfacing for all types of vehicle at study sites. Observations and further analysis revealed that passenger cars often struggle to keep pace with commercial vehicles on road with poor surfacing. Traffic flows are worst when passenger cars are the platoon leaders. Therefore, the problem of passenger car equivalency values in roadway capacity analysis cannot however be ignored. On the one hand it shows the potential of commercial vehicles gaining control of roadway by exploiting the presence of poor pavement as shown in the study. On the other hand it exposed the weakness of passenger cars as mode of transport on distressed road surfaces. Given good road surface, drivers may travel at higher speeds given a certain traffic density, may keep shorter distances between vehicles ahead without lowering speed, or may choose a different lane of the carriageway. In fact drivers may even elect to change routes or departures times because of improved road and traffic conditions. For drivers who are familiar with the terrain and positioning of the defects, the travel time over the length of such road may somehow be slightly different to those who are new to or irregular users of the road.

In considering the mechanisms by which severe road surfacing condition may possibly influence roadway capacity, two groups of factors seem most important: the changing behaviour of drivers and the changing composition of traffic under prevailing conditions. Thus, when computing highway capacity, mixed vehicle volumes are usually converted into passenger car equivalency flows by taken into account vehicle type, road, traffic and ambient conditions. Ignoring PCE modifications or recalibration could lead to grossly inaccurate road capacity estimates with attendant consequences for transportation modelling.

## 6. SET UP OF FIELD STUDY

Empirical studies has shown that speed decreases exponentially with increase in density, however, it can be hypothesised that since highway capacity on road sections with poor surface conditions will be significantly different from that of the sections with good surfaces, PCE values for both sections would not be the same. In Malaysia, express, principal, state and residential roads are considered as possible study site options. Since the study relied on improvised temporary vertical deflections (ramps) across road widths, expressways and principal roads were rule out for safety reasons and regulations that ban putting ramps on such roads.

Land use, traffic and environment data were collected from sample state and residential roads. Within the objectives of the study and the site boundaries, roads were selected based on the following criteria:

- Road Geometry ≥ class 'B' road with clear visibility, level terrain and the absence of traffic signals influence
- Road Link ≥ 500m to allow for survey length > 210m, surface distress length (variable) and transition length = 160m after surface distress. The link should be free both ways of influence from road junction, roundabout, petrol station, broken down or parked vehicle, police check point and other roadway/traffic conditions that could cast doubt on data collected.
- Road must not be impaired traffic movements like on street parking, traffic signals and also sections that are free from vertical deflection not too far out of range for meaningful speed-flow measurements

The sample roads were ranked; as a result, six sites were selected knowing fully well that the study approach can be applied to all the sites with reliable outcomes. Typical survey site set up is shown below in figure 3.

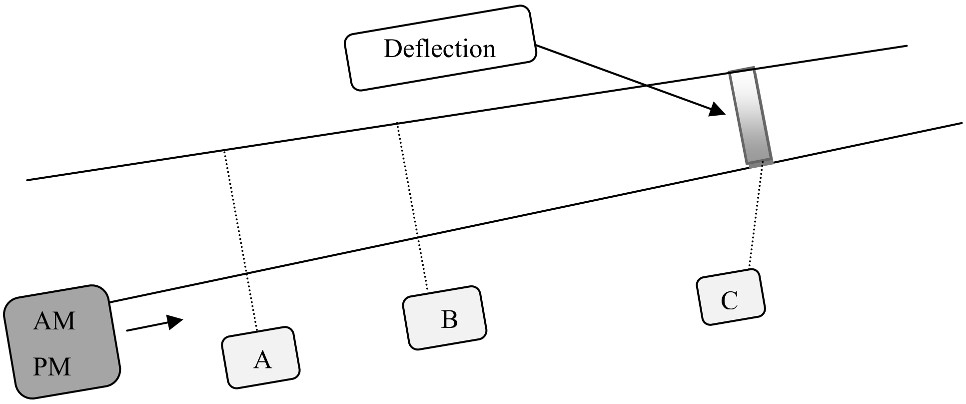


Figure 3 Typical Survey Site setup

As shown above in figure 3, study sites were divided into three sections with *Section **A*** as the upstream end and *Section **C*** the downstream end, while *Section **B*** was the transition part allowing for possible traffic congestion. *Section B* was set at 130m from the baseline of section A and B. Point A is spaced at 50m from B; and B is 130m from C; The spacing of road sections commenced from section C to B where the sighting distance of motorists was first estimated using observed average free flow speed of 90km/h or 55mph taken at point A. Assuming 5% gradient (G), 2.5seconds reaction time (t), 0.30 coefficient of friction (f), and stopping distance, $S = 0.278Vt + 0.039\ V^2 / a \approx 130\text{m}$ Where: V = design speed, mph (km/h), t = brake reaction time, 2.5 s, a = driver deceleration, $\text{m/s}^2$.

The upstream end (section A) is the section with good surface while the downstream end (section C) is the section with vertical deflection in form of edge to edge round top humps 100mm high in the direction of traffic. Volume and speed and vehicle type data were collected using automatic traffic counter for 30 days. Data on the peak and off peak periods collected at the initial stage were used to establish the observation time period in order to eliminate the effect of peak period on capacity because the primary focus is an uninterrupted flow. Data relating to rainfall were used to exclude rainy periods. Thus the influence of rain on capacity was eliminated and surveys were conducted during daylight to eliminate the effect of darkness.

Initial test runs and analysis were carried out randomly at location J008; influence of round top humps on speed were tested at 75mm, 100mm and 150mm in order to establish an appropriate study height, experienced gained proved invaluable when full study was conducted.

## 7. FIELD STUDY RESULTS AND ANALYSIS

The main aim to determine capacity and level of service for 6 surveyed sites based on equation 2 shown below. The objectives are as follows: Determine traffic flow from vehicle volume and density from the speed / flow relationship relying on the fundamental diagram then use the flow and density relationship to determine the capacities for road sections A and B; extrapolate optimum speeds from the computed capacities to determine level of service.

$$q = -\beta_o + \beta_1 k - \beta_2 k^2 \qquad (2)$$

By computing roadway capacity for each link section, it is recognised that capacity varies per road section and the method used for estimating capacities is based on the fundamental relationship between flow, speed and density. In the flow ($q$) – density ($k$) relationship density is used as the control parameter and flow is the objective function.

However, before roadway capacity can be estimated it is important that the effect of mixed traffic is taken into consideration and this was done by way of volume conversion into passenger car equivalency units. PCE is usually the terminology employed in the United States and Canada, while PCU is commonly used in the United Kingdom. PCE and PCU are same. Compare the capacities in section A and B to establish whether a loss resulting from modified PCE values has occurred.

The calculation of capacity by way of quadratic function is incomplete without determining the point of the extrapolated curve that represents the capacity and this point is a function of critical density. This critical density can be derived, estimated or assumed as appropriate. It is quite possible to extrapolate mathematically until the maximum of the q-k function is attained, but how will such theoretical values compare with reality of traffic operations? The calculated capacities may be unrealistically high and questionable. It can be argued that capacities so derived may very little resemblance to traffic conditions.

In any case empirical density is often difficult to determine because one should observe a complete and uniform road section and count the total number of cars present at any moment. Instead, local density is used in the calculations. An assumed critical density can be used to calculate the corresponding rate of flow. But it has to be known. So it is now obvious that an assumed critical density value and mathematical model of critical density cannot be made in this case in the light of the stated poor surface conditions, hence the need to estimate critical density. In the analysis only data per carriageway lane were used, therefore the estimated capacities are carriageway lane capacities. Tables 1 and 2 contain some of the variables used for capacity analysis.

The effects of pavement distress on passenger car equivalent values are significant and must be taken into account when determining flow at road section with pavement distress. From observation at surveyed sites, trucks are less affected by pavement distress than passenger car and it may be argued that the passenger car equivalent values of trucks or HGVs are somewhat lower than those of passenger cars on roadways with significant pavement distress.

It can be mentioned in passing that there was a sharp difference in the attitude of heavy goods vehicle (HGV) drivers on road section with surfacing distress. HGV motorists pay very little attention to pavement distress as observed at surveyed sites. It may be argued that because of change in drivers attitude relative to pavement distress, and to some extent the need by heavy goods vehicle (HGV) operators to make profit, a description that depict passenger car equivalency value for HGV as substantially higher than one unit on distressed level terrain is somehow distorted. Also, the extent to which HGV vehicles are driven at an above average speed on such terrain would give to claim that HGV passenger car unit is about one unit sometimes lower than one unit.

The study employed a simplistic approach based on Greenshields (*1934*) headway method of calculating PCE between vehicles under saturated flow conditions as:

$$PCE_{ij} = H_{ij} / H_{pcj}$$

Where, *$PCE_{ij}$ is the PCE of vehicle Type i under Conditions j, and $H_{ij}$, $H_{pcj}$ is the average headway for vehicle Type i and passenger car for Conditions j.* The results of the computed PCE values are shown below in Tables 1 & 2. By using the headway method one is implying that the relative amount of space occupied by a vehicle in motion is the basis for calculating PCE values. Same PCE estimation method was applied to the road section with vertical deflection for the purpose of consistency in application.

From observations at survey sites, passenger cars sometimes force HGVs to slow down especially when they are platoon leaders because of their manoeuvrability difficulties on road sections with vertical deflection. These observations further validate the definition of PCE values and to some extent the reason why the PCE values of HGVs and LGVs could be slightly less than 1.0 given unfavourable conditions. It is worth noting that PCE values are dynamic and tasked with presenting the effect of mixed traffic stream for capacity and level of service analysis.

**Table 1** Estimated PCE values for Good Road Section

| Site | Vehicle Type | Speed m/sec | Density Veh/hr | Spacing M/veh | Headway sec/veh | PCE unit |
|---|---|---|---|---|---|---|
| 004 | PC | 22 | 28 | 35.714 | 1.623 | 1.000 |
| | LGV | 17 | 28 | 35.714 | 2.101 | 1.294 |
| | HGV | 11 | 28 | 35.714 | 3.247 | 2.000 |
| 005 | PC | 22 | 22 | 45.455 | 2.066 | 1.000 |
| | LGV | 18 | 22 | 45.455 | 2.525 | 1.222 |
| | HGV | 13 | 22 | 45.455 | 3.497 | 1.692 |
| 006 | PC | 22 | 31 | 32.258 | 1.466 | 1.000 |
| | LGV | 17 | 31 | 32.258 | 1.898 | 1.294 |
| | HGV | 15 | 31 | 32.258 | 2.151 | 1.467 |
| 008 | PC | 22 | 34 | 29.412 | 1.337 | 1.000 |
| | LGV | 19 | 34 | 29.412 | 1.548 | 1.158 |
| | HGV | 15 | 34 | 29.412 | 1.961 | 1.467 |
| 009 | PC | 24 | 32 | 31.250 | 1.302 | 1.000 |
| | LGV | 16 | 32 | 31.250 | 1.953 | 1.500 |
| | HGV | 14 | 32 | 31.250 | 2.232 | 1.714 |
| 011 | PC | 24 | 26 | 38.462 | 1.603 | 1.000 |
| | LGV | 17 | 26 | 38.462 | 2.262 | 1.411 |
| | HGV | 14 | 26 | 38.462 | 2.747 | 1.714 |
| PCE | PC = 1.00 | | LGV 1.37±0.04 | | HGV = 1.75±0.07 | |

**Table 2** Estimated PCE values for Poor Road Section

| Site | Vehicle Type | Speed m/sec | Density veh/hr | Spacing m/veh | Headway sec/veh | PCE Unit |
|---|---|---|---|---|---|---|
| 004 | PC | 10.56 | 50 | 20.000 | 1.895 | 1.000 |
| | LGV | 11.11 | 50 | 20.000 | 1.800 | 0.950 |
| | HGV | 10.83 | 50 | 20.000 | 1.846 | 0.974 |
| 005 | PC | 10.83 | 31 | 32.258 | 2.978 | 1.000 |
| | LGV | 11.11 | 31 | 32.258 | 2.903 | 0.975 |
| | HGV | 10.56 | 31 | 32.258 | 3.056 | 1.026 |
| 006 | PC | 10.28 | 56 | 17.857 | 1.737 | 1.000 |
| | LGV | 10.83 | 56 | 17.857 | 1.648 | 0.949 |
| | HGV | 10.28 | 56 | 17.857 | 1.737 | 1.000 |
| 008 | PC | 10.83 | 48 | 20.833 | 1.923 | 1.000 |
| | LGV | 11.94 | 48 | 20.833 | 1.744 | 0.907 |
| | HGV | 11.11 | 48 | 20.833 | 1.875 | 0.975 |
| 009 | PC | 09.72 | 51 | 19.608 | 2.017 | 1.000 |
| | LGV | 10.56 | 51 | 19.608 | 1.858 | 0.921 |
| | HGV | 10.00 | 51 | 19.608 | 1.961 | 0.972 |
| 011 | PC | 10.56 | 51 | 19.608 | 1.858 | 1.000 |
| | LGV | 10.83 | 51 | 19.608 | 1.810 | 0.974 |
| | HGV | 10.56 | 51 | 19.608 | 1.858 | 1.000 |
| PCE | PC = 1.00 | | LGV=0.95±0.01 | | HGV=0.98±0.01 | |

After computing PCE values based on survey data, they were used to estimate highway capacities for road section with and without good surface. Equation 2 was relied on for quantitative measurements as shown below;

$$q = -\beta_o + \beta_1 k - \beta_2 k^2 \quad (2)$$

By differentiating flow wrt density equation 2 can be rewritten as:

$$\partial q / \partial k = \beta_1 - 2\beta_2 k$$

By setting $\partial q / \partial k = 0$;

Determine critical density ($k_c$), and then plug $k_c$ into equation 2 to determine maximum flow ($q_m$)

$$q_m = -\beta_o + \beta_1 k_c - \beta_2 k_c^2$$

Test model equations for statistical fit at 5% level of significance
Determine the optimum speeds

For $q = uk$;

Optimum Speed, $u_0 = q_m / k_c$

### 7.1 Sample calculations for site J008

Road without vertical deflection section A

$$q_A = -1.5755k^2 + 105.47k - 59.044$$
$$\partial q / \partial \kappa = 2(-1.5755k) + 105.47 = 0$$
$$\kappa_{crt} = 34 \text{ veh/km}$$
$$q_A = -1.5755(34)^2 + 105.47(34) - 59.044$$
$$q_A = 1706 \text{ pcu/hr}$$
$$u_o = 1706/34 \approx 50 \text{ km/h}$$

Road with vertical deflection section B:

$$q_B = -0.5022k^2 + 47.701k - 10.25$$
$$\partial q / \partial \kappa = 2(-0.5022k) + 47.701 = 0$$
$$\kappa_{crt} = 48 \text{ veh/km}$$
$$q_B = -0.5022(48)^2 + 47.701(48) - 10.25$$
$$q_B = 1123 \text{ pcu/hr}$$
$$u_o = 1123 / 48 \approx 23 \text{ km/h}$$

Optimum speeds were extrapolated from the computed capacities. By computing roadway capacity for each link section, it is recognised that capacity varies per road section and the method used for estimating capacities is based on the fundamental relationship between flow, speed and density. In the flow (*q*) – density (*k*) relationship, density is used as the control parameter and flow is the objective function. Summary of the model coefficients for all surveyed sites are shown below in Table 3.

**Table 3** Summary of Model Coefficients

| Site | | Density $-\beta_o$ | Speed $\beta_1 k$ | Flow $-\beta_1 k^2$ | $R^2$ |
|---|---|---|---|---|---|
| J001 | Without VD | 158.26 | 103.22 | 2.0398 | 0.87 |
| | With VD | 43.569 | 51.853 | 0.6396 | 0.96 |
| J002 | Without VD | 14.001 | 103.22 | 2.4680 | 0.95 |
| | With VD | 124.48 | 61.456 | 0.9628 | 0.98 |
| J003 | Without VD | 91.271 | 113.61 | 2.0224 | 0.97 |
| | With VD | 140.11 | 58.934 | 0.6886 | 0.97 |
| J004 | Without VD | 56.201 | 106.22 | 1.7856 | 0.96 |
| | With VD | 4.5358 | 46.901 | 0.6113 | 0.95 |
| J005 | Without VD | 52.064 | 111.86 | 1.9201 | 0.96 |
| | With VD | 107.66 | 57.765 | 0.8927 | 0.96 |
| J006 | Without VD | 102.12 | 128.85 | 2.6756 | 0.98 |
| | With VD | 73.528 | 52.704 | 0.6681 | 0.98 |

Test statistics for model equations in the study are found to be reliable at 5% level of significance, all r are greater than 0.5, ts' greater than 2.5 and Fs' greater than 10.0 Computed highway capacities and LOS analysis for all sites are summarised below in tables 4 and 5.

**Table 4** Summaries of Highway Capacity & LOS Analysis – Section A

| Site | Static PCE Values | | | | Dynamic PCE Values | | | |
|---|---|---|---|---|---|---|---|---|
| | Highway Capacity pcu/h | Critical density veh/km | Optimum speed km/h | LOS | Highway Capacity pcu/h | Critical density veh/km | Optimum speed km/h | LOS |
| J001 | 1555 | 28 | 56 | B | 1650 | 29 | 56 | B |
| J002 | 1111 | 22 | 51 | B | 1065 | 21 | 51 | B |
| J003 | 1663 | 31 | 54 | B | 1504 | 28 | 54 | B |
| J004 | 1706 | 34 | 50 | B | 1523 | 30 | 51 | B |
| J005 | 1713 | 32 | 54 | B | 1577 | 29 | 54 | B |
| J006 | 1560 | 26 | 60 | A | 1449 | 24 | 61 | A |

**Table 5** Summaries of Highway Capacity & LOS Analysis – Section B

| Site | Static PCE Values | | | | Dynamic PCE Values | | | |
|---|---|---|---|---|---|---|---|---|
| | Highway Capacity pcu/h | Critical density veh/km | Optimum speed km/h | LOS | Highway Capacity pcu/h | Critical density veh/km | Optimum speed km/h | LOS |
| J001 | 1204 | 50 | 24 | E | 1007 | 41 | 25 | E |
| J002 | 849 | 31 | 27 | D | 856 | 32 | 27 | D |
| J003 | 1468 | 56 | 26 | D | 1121 | 43 | 26 | D |
| J004 | 1122 | 48 | 23 | E | 895 | 38 | 23 | E |
| J005 | 1195 | 51 | 23 | E | 827 | 32 | 26 | D |
| J006 | 1244 | 51 | 24 | E | 966 | 39 | 24 | E |

From tables 4 and 5 above, it can be seen that capacities at section A are substantially higher than those at section B for all investigated sites. Also critical densities at road section B were significantly higher than those at section A. Vehicles operating at road section A were completely unaffected by the road hump. They were almost completely unimpeded in their ability to manoeuvre within the traffic stream because the operating conditions afford the driver higher speeds. Whereas at road section B drivers were operating at lower speeds because freedom to manoeuvre within the traffic stream was limited due to poor surfacing.

Because critical densities have been found to be higher at the road section B; it follows that spacing would be smaller. Speeds on this road section for all types of vehicles are almost the same because all the vehicles were constrained by the same road conditions with very little room for manoeuvrability. Thus, given smaller spacing, lower speed, and larger density, it's to be expected that the PCE values for road sections with vertical deflection would be somewhat lower than that of the section without vertical deflection.

The estimated PCE values for road section A, were found to be lower than those presently used for most of the standard capacity analysis (PC=1, LGV=1.5 HGV=2.1) and this may not be unconnected with the low level of traffic volume. This may call to question the appropriateness of the static Malaysia PCE values. However, the derived PCE values are preliminary findings and separate large scale studies are needed in order to derive a true reflective PCE values.

Notwithstanding, investigation into the application of passenger car equivalency values in highway capacity and level of service analysis has revealed that: i) poor road surfacing has significant effects on PCE values; ii), given poor road condition, PCE values for HGV are not substantially higher than 1; iii) That the estimated highway capacity are affected PCE values; iv) LOS is unaffected by PCE values.

In the Highway Capacity Manual-HCM, level-of-service (LOS) is taken as a measure-of-effectiveness. It uses the letters A through F to describe prevailing road traffic condition, with A being best and F being worst., The suggestion that LOS A to E have optimum speed commonality as shown in many literatures distorts assertion that congested and uncongested capacities have different optimum speeds as shown in the paper. According to HCM 2000 LOS E is a marginal service state. Flow becomes irregular and speed varies rapidly, but rarely reaches the posted limit. On highways this is consistent with a road operating over its designed capacity.' Is HCM 2000 suggesting that LOS is based on design capacity that can be exceeded by absolute capacity?

Clearly, under LOS E condition, the roadway is at capacity. However, the problem with LOS E is that absolute capacity is exceeded because the bottom range of LOS E is below optimum speed ($u_0$), when it should have terminated at $u_0$. LOS E description distorts negative linearity rule of lower boundary termination at maximum flow. HCM 2000 further introduced negative diagonal speed-flow curves suggesting that corresponding concave capacity shifts will occur along several lines with the same optimum speed. Again this is doubtful.

Further, HCM 2000 suggested that 'LOS F is the lowest measurement of efficiency for a road's performance. Flow is forced; every vehicle moves in lockstep with the vehicle in front of it, with frequent drops in speed to nearly zero kph'. Technically, a road in a constant traffic jam would be at LOS F, because LOS does not describe an instant state, but rather an average or typical service'. In sum, highway traffic flow can be categorized into two modes, uncongested and congested. Uncongested traffic mode depicts a highway where traffic demand is less than the absolute capacity, vehicle speeds oscillating between optimum and free flow speed limits under prevailing conditions. Whereas congested traffic mode depicts a highway where capacity is over sub-subscribed, speeds become unpredictable, quality of service significantly reduced, vehicles are herd and synchronised.

From the discussion it can be seen that roadway capacity analysis and their attendant PCE values encapsulate effects resulting from three variables, namely density, speed and flow under prevailing conditions. Even though attempts have been made by many scholars to address the issues of passenger car equivalency and provide more realistic values for uninterrupted flow, there are no uniform values. So, by using a simplistic 'headway of vehicle type' approach we can at least point PCE values in a particular direction.

## 7 CONCLUSIONS

Although several capacity-estimation methods are based on appropriate theories concerning macroscopic traffic flow, the attempts to determine the capacity of a road by existing methods will generally result in a capacity value estimate. The validity of this value is hard to investigate because of the lack of a reference capacity value, which is supposed to be absolutely valid. Nevertheless the chosen method in the paper would be sufficient in determining capacity in case where capacity is seldom reached. The paper has shown that road conditions among others have implications for PCE values, so it can be concluded that:

- There is a significant change in roadway capacity resulting from PCE adjustments.
- Capacity is generally higher with standard PCE values compared to adjusted PCE values.
- There is no significant change in level of service due to adjusted PCE values.
- There is no other factor other than vertical deflection that affected capacity and LOS changes.
- The hypothesis that vertical deflection has influence on PCE values remains valid.
- The hypothesis that capacity and LOS loss would result from vertical deflection remain valid.

The conclusions drawn follow from the application of PCE values in highway capacity and level of service analysis. Further research is needed to ascertain the reliability of PCE values under prevailing conditions. In this study headway was estimated from spacing and speed, it would be useful to conduct a larger headway distribution survey for vehicle types under varying conditions.

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